AD-A047 065 WEAPONS RESEARCH ESTABLISHMENT SALISBURY (AUSTRALIA) F/G 9/3
PROCESSING SPECTROGRAMS AS DIGITAL PICTURES TO SEPARATE COMPETI--ETC(U)
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UNCLASSIFIED WRE-TR-1763(W) NL

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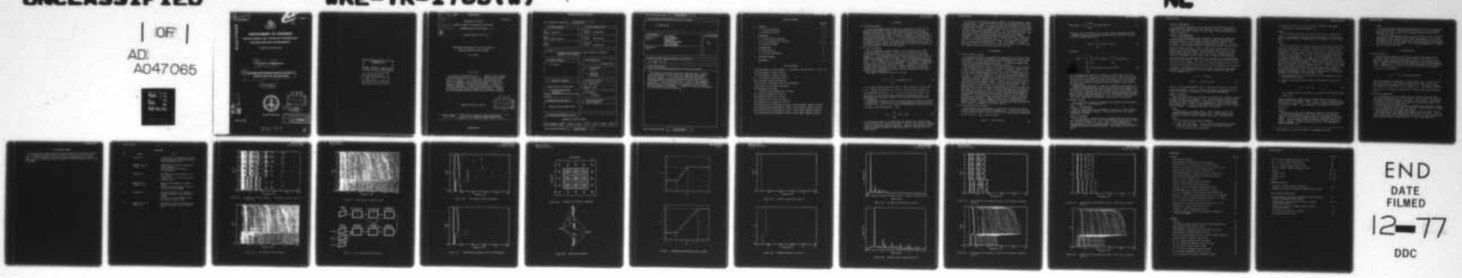

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(14) WRE-TR-1763 (W)

AR-000-513

AD A 047065

AUSTRALIA

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

WEAPONS RESEARCH ESTABLISHMENT

SALISBURY, SOUTH AUSTRALIA

(9) TECHNICAL REPORT, 1763 (W)

(6) PROCESSING SPECTROGRAMS AS DIGITAL PICTURES TO SEPARATE COMPETING LINE SIGNATURES.

(10) D.G. NICHOL

(12) 24p.

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Approved for Public Release.

(11) FEBRUARY 1977

COPY No. 64

371 700

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TECHNICAL REPORT 1763(W)

PROCESSING SPECTROGRAMS AS DIGITAL PICTURES TO SEPARATE COMPETING LINE SIGNATURES

D.G. Nichol

S U M M A R Y

The problem of extracting individual signatures from a (digital) spectrogram containing two or more line signatures amidst random noise is discussed. It is assumed that each signature family contains a dominant line and the method proposed is based on using line enhancement and grouping procedures to isolate these dominant components. Using the extracted lines a family of two-dimensional matched filters are designed for each signature and used to detect the weaker members of the family. Cleaned-up low-entropy spectrograms of each source can then be produced.

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Box 2151, G.P.O., Adelaide, South Australia, 5001.

DOCUMENT CONTROL DATA SHEET

Security classification of this page: UNCLASSIFIED

1 DOCUMENT NUMBERS	
AR Number:	AR-000-513
Report Number:	WRE-TR-1763(W)
Other Numbers:	

2 SECURITY CLASSIFICATION	
a. Complete Document:	UNCLASSIFIED
b. Title in Isolation:	UNCLASSIFIED
c. Summary in Isolation:	UNCLASSIFIED

3 TITLE

PROCESSING SPECTROGRAMS AS DIGITAL PICTURES TO SEPARATE COMPETING LINE SIGNATURES

4 PERSONAL AUTHOR(S):

D.G. Nichol

5 DOCUMENT DATE:

February 1977

6 6.1 TOTAL NUMBER OF PAGES 24

6.2 NUMBER OF REFERENCES: 6

7 7.1 CORPORATE AUTHOR(S):

Weapons Research Establishment

7.2 DOCUMENT (WING) SERIES AND NUMBER

Weapons Research and Development Wing

TR-1763

8 REFERENCE NUMBERS

a. Task: DST/75/047

b. Sponsoring Agency: RD69

9 COST CODE:

331-343586

10 IMPRINT (Publishing establishment):

Weapons Research Establishment

11 COMPUTER PROGRAM(S) (Title(s) and language(s))

12 RELEASE LIMITATIONS (of the document):

Approved for Public Release

12.0	OVERSEAS	NO		P.R.	1	A		B		C		D		E	

Security classification of this page: UNCLASSIFIED

Security classification of this page: UNCLASSIFIED

13 ANNOUNCEMENT LIMITATIONS (of the information on these pages):

No limitations

14 DESCRIPTORS:

a. EJC Thesaurus Terms

SPECTROGRAMS
DATA PROCESSING
RANDOM NOISE
SPECTRUM SIGNATURES
LINE SIGNATURES
DIGITAL PICTURES

b. Non-Thesaurus Terms

15 COSATI CODES:

1402

16 LIBRARY LOCATION CODES (for libraries listed in the distribution):

SW, AACA, SR, SD

17 SUMMARY OR ABSTRACT:
(if this is security classified, the announcement of this report will be similarly classified)

The problem of extracting individual signatures from a (digital) spectrogram containing two or more line signatures amidst random noise is discussed. It is assumed that each signature family contains a dominant line and the method proposed is based on using line enhancement and grouping procedures to isolate these dominant components. Using the extracted lines a family of two-dimensional matched filters are designed for each signature and used to detect the weaker members of the family. Cleaned-up low-entropy spectrograms of each source can then be produced.

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1. OVERVIEW

1.1 The general problem

In a previous paper(ref.1), which will be referred to as Paper 1, the problem of processing a digital spectrogram containing a time-variant signature consisting of related lines and broad-band noise was discussed. The aims were two-fold: firstly to detect and enhance the weaker members of the line family, and secondly to produce a cleaned-up low-entropy spectrogram suitable for machine analysis. In the present paper the problem is extended to consider the case where more than one family of lines is present. The aims here are initially to unscramble the mixed signatures and then, as discussed in Paper 1, detect the weak structure and produce good quality low-data spectrograms of each source individually.

1.2 Problem constraints

The line-signatures considered are of a type characteristic of many vibrational/rotational sources. That it, it is assumed there is some driving function at the fundamental frequency which excites higher order harmonics. If the fundamental driving frequency changes with time then the higher-order harmonics mimic this change. On a spectrogram plot this produces a 'related family' of lines, often immersed in broad-band background noise. It is assumed that one of the members of the family is significantly stronger (say 2 to 10 dB) than the remainder. Furthermore, the members of the family shall not be restricted to (integer) harmonics but other non-integer related lines may be present. (These could arise from gearing reduction noise for example and such lines occur frequently in the sorts of signals under consideration.)

The signals of interest are thus of the form:

$$s_l(t) = \sum_{k=1}^{K} a_k \exp i2\pi b_k \alpha_l(t)t \qquad (1)$$

It is assumed that the amplitudes, the a_k's above, change only slowly with time. Suppose the dominant line is $k = k'$, then the order constants b_k are normalised such that $b_k' = 1$. In this case then the function α (t) represents the locus of the centre frequency of the dominant line. No phase terms are included in equation (1) as the power spectrum only will be considered.

Consider the case where at least two sources such as described by equation (1) are present. The input x(t) to the spectral analyser thus consists of L signals, $s_1(t)$, $s_2(t)$,...$s_L(t)$, plus a broad-band noise process n(t) which we assume is white and additive. Thus:

$$x(t) = \sum_{l=1}^{L} s_l(t) + n(t) \qquad (2)$$

For the present paper it is assumed that the dominant lines of each source do not intersect in the observation interval and also that different dominant lines do not have the same time variation. However, the secondary (weaker) lines are allowed to intersect either the dominant or secondary lines of other sources.

As in Paper 1 the signatures used as examples come from automobile engine noise emissions. Figure 1(a) and 1(b) shows the spectrograms of two sources recorded alone and figure 1(c) shows the spectrogram obtained by mixing the signals before analysis. It should be noted that white noise has been added to figure 1(b). The spectrogram of figure 1(c) was stored and used as the input to the signature separation process. The signal shown in figure 1(b), was used in Paper 1 and consists almost entirely of integer harmonics. The other signal is more complex containing both integer and non-integer 'harmonics'. The quasi-periodic falls in engine speed seen in figure 1(a) are due to a thermostatic fan cutting in. As the fan's speed is constant the 'fan-line' (near 200 Hz) does not change in frequency when the engine speed is increased (at approximately t = 140 s for example). However, as the overall shape of the fan-line is similar to the engine lines, this makes this example a severe test of the detection algorithms.

2. METHODOLOGY

2.1 Picture analysis approach

The spectra of figure 1 are produced by computing the Fast Fourier Transform (FFT) and then the periodogram of successive data blocks from the time series(ref.2). In this case a data block of 1024 points is used so each 'row' of the spectrogram contains 512 points. In all these examples 200 successive spectra are plotted to form the spectrogram.

The approach adopted in Paper 1 is to treat the spectrogram as a digital picture, containing in this case 200 rows and 512 columns. There is thus a total of 102,400 picture elements of 'pels'. From equation (1) it is seen that each signature family consists of a series of related lines, and if one of these could be found this will lead to the possible positions of the others. The method proposed is to use line enhancement and detection techniques to find the dominant line in each family and to use this as a 'template' to design a family of matched filters which can be used to detect other members of the signature family. However, the presence of several families requires modification of this scheme because the dominant lines of other families are so strong that they can cause 'false alarms'. The modified scheme is shown in figure 2 and described in detail in Section 2.3. Basically, as in Paper 1, a search is made for dominant line structure, but the presence of at least two such lines means more sophisticated grouping and joining techniques must be used. Having found the desired number of dominant lines all except one are (temporarily) removed from the analysis spectrogram. This spectrogram is then processed as in Paper 1 using the remaining line's template. Having produced a clean spectrogram for the family corresponding to this template, the process is repeated for each template in turn. Before discussing the line detection problem the matched filter scheme is considered a little more closely.

2.2 Use of matched filter families

Each estimate in the spectrogram is derived from the short term Fourier transform of the input function x(t) equation (2). If the acquisition time for this transform buffer is T then the row of the spectrogram corresponding to the interval $(t - \frac{T}{2}, t + \frac{T}{2})$ is given by

$$p(f,t) = X(f,t)\,X^*(f,t) \qquad (3)$$

where $$X(f,t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} x(\tau)\exp(-i2\pi f\tau)\,d\tau \tag{4}$$

and where t runs in discrete steps over the complete observation interval.

Denoting the short term Fourier transform of $s_l(t)$ and $n(t)$ by $S_l(f,t)$ and $(N(f,t)$ respectively leads to

$$X(f,t) = \sum_{l=1}^{L} S_l(f,t) + N(f,t) \tag{5}$$

and hence

$$p(f,t) = \sum_{l=1}^{L}\sum_{m=1}^{L} S_l(f,t)\,S_m^*(f,t) + \sum_{l=1}^{L} S_l(f,t)N^*(f,t)$$

$$+ \sum_{l=1}^{L} S_l^*(f,t)\,N(f,t) + N(f,t)\,N^*(f,t) \tag{6}$$

The spectrogram thus consists of L families of related lines (the first term in equation (6)) superposed on a noise process. Since the last term in equation (6) is a nearly white noise process(ref.3) and the cross-power terms are zero outside the signal bins, a two-dimensional filter matched for white noise should significantly enhance the signal-to-noise ratio of the spectrogram.

Moreover, since each family of lines has a different time-variation then a correlation detection process (such as the matched filter) designed for one family will in general tend not to respond to lines from another. However for very strong competing lines this may not be so, and to reduce the chance of false alarms all dominant lines are removed from competing families before applying the detection process. This is repeated in turn for each family and a low-entropy spectrogram for each source can be produced.

2.3 Template assembly

The scheme used to extract the dominant lines from the raw spectrogram is shown in figure 2. The stages are:

Stage 1: Pre-processing

Remove a running mean over a rectangle of size m x n. This is done to remove any broad signal structure. The size used by this was usually 7 (frequency) x 3(time).

Stage 2: Thinning

As the spectrum of a sweeping line is broadened, then each line tends to cover several bins(refs.1,4). To aid the thresholding discussed in stage 3 it is necessary to 'thin' each line. This is done as suggested by Rosenfeld(ref.5), that is by suppressing pels in a given row if there is a stronger one within a prescribed distance. The distance used here was ± 2 pels.

Stage 3: Thresholding

If the dominant structure is 2 dB or more above the noise then simple thresholding can extract much of the structure. Thus, in figure 3(a) all except the four strongest points have been removed from the de-meaned and thinned spectrogram.

Stage 4: Line Enhancement

A local line enhancement scheme, based on the line-feature extraction scheme of Moore and Parker(ref.6), is used as in Paper 1 to process the thresholded picture. This removes isolated points and enhances line structure. This scheme is described in more detail in Paper 1. Briefly, the method involves computing the local angular distribution function $F_\theta(f,t)$ on the thresholded picture. That is, take a local region of size m by n centred on (f,t) and (figuratively) draw straight lines from (f,t) to all non-zero points in this region. The distribution of the slopes of these lines is then evaluated. Now if (f,t) lies on line structure then the resulting distribution function $F_\theta(f,t)$ has a strong peak corresponding to the slope of the line, whereas if (f,t) is away from a line the distribution tends to be more uniform. Thus if we have a function Y_θ of the distribution function F_θ which produces high values for peaky distributions and low values for uniform distributions this can be used on the calculated F_θ for each point to produce a line-enhanced version of the stage 3 thresholded spectrogram. Figure 3(b) shows the output Y_θ of such a process applied to figure 3(a). For this example we use

$$m = n = 19 \text{ and}$$

$$Y_\theta(f,t) = p(f,t)^{\frac{1}{2}} n_x/(mn) \tag{7}$$

where n_x is the maximum number of pels in one angle bin of $F_\theta(f,t)$ and p(f,t) the raw spectrogram. The line structure has clearly been enhanced by the process and the non-line structure can be removed by thresholding.

Stage 5: Grouping

Looking at figure 3(b) it is clear that not all the line structure accepted by stage 4 belongs to the dominant lines. Furthermore not all parts of the dominant lines have been detected. A procedure is needed to group together the various pieces of dominant line structure and to reject structure belonging to weaker lines. This is a much more difficult task for a serial machine than for a human. The approach used here is as follows.

Step A

Find and label all primary groups. That is groups consisting of immediate neighbours as shown in figure 4(a). Note that due to the thinning of stage 2, primary neighbours only occur in different rows.

Step B

For each primary group find the following:

(i) 'head' and 'tail' pels. That is, the first and last pel in each group (see figure 4(b)). For the k-th group denote these by (f_1^k, t_1^k) and (f_2^k, t_2^k) respectively.

(ii) the mean value, $\tilde{Y}_\theta$, of $Y_\theta(f,t)$ for the elements of each group, where $Y_\theta(f,t)$ is given by equation (7).

Step C

Find the primary group with the largest value of $\tilde{Y}_\theta$. Suppose this is group j. This group is then used as the starting point for the search for the larger grouping (the 'mega-group') corresponding to each dominant line.

Step D

Find the distances from the head of group j to the tails of each other group (see figure 4(b)). Denote the magnitude of the frequency separation by Δf and the time separation by Δt. Now we wish to find the primary group which is "closest" to group j and choose this as the most probable next member of our mega-group. However, the Euclidean distance is not a suitable measure, because it does not allow for our a priori knowledge of the dominant line behaviour. We know, for instance, that for the cases of interest sudden changes in frequency are rare, whereas due to transitory noise, or fluctuating signal strength, the dominant line will suffer from gaps in time fairly frequently. Thus we wish to weight* small time gaps Δt less heavily than small frequency gaps Δf. However, we also know that large changes in frequency can occur (as at t = 130 s in figure 1(b)), so in order to avoid missing these we weight large shifts Δf no more heavily than large gaps in Δt. From such heuristic considerations the weighted conversion plots shown in figure 5 were derived. The method of choosing the next member of the mega-group is thus

(1) having found Δf and Δt for all groups, find the weighted equivalents $\Delta f'$ and $\Delta t'$ from figure 5.

(2) choose as the next member the group with the lowest 'separation' d_s where

$$d_s = \Delta t' + \Delta f' \quad (8)$$

If two groups have the same value of d_s choose the one with the higher value of $\tilde{Y}_\theta$.

Having found the next member this can then be used, as group j was, to search for the next 'upwards' member. That is step D is repeated using the new group j' instead of j. This process is continued until no groups with finite d_s remain. The mega-group is now complete in the upwards direction.

Step E

Now proceed to look for the 'downwards' members of the mega group. Start again at the dominant primary group j but this time evaluate separation Δt and Δf from the tail of group j to the heads of the other groups. These are then weighted and used in exactly the same way as in Step D. We thus eventually find all downwards elements and the mega-group is complete. Figure 6(a) shows the first of the mega-groups found from figure 3(b).

*All 'weighting' in this section means 'unfavourable weighting'.

Step F

At this point the mega-group corresponding to the first of the dominant lines has been found. This can then be 'filled-in' by a line tracking algorithm and a more accurate centre-frequency estimate found by interpolation as in Paper 1.

To find the other dominant lines all primary groups forming the detected mega-group are then removed from the stage 4 spectrogram. The resulting spectrogram is then processed exactly as described above starting at Step A. This whole process is then repeated until the required number of mega-groups, and dominant lines has been found. The second mega-group found in figure 3(b) is shown in figure 6(b).

3. IMPLEMENTATION

3.1 Line detection

Having found the dominant lines, and interpolated their position more accurately, these can be used as described in Paper 1 and Section 2.2 to detect the weaker structure by designing a family of filters from each template and applying these to the raw spectrogram minus the remaining dominant lines. Suppose the 1-th filter of the family corresponding to k-th dominant line is described by $g_{1k}(f,t)$ then if this is applied to the spectrogram equation (6), the output is

$$z_{1k} = \Sigma\,\Sigma\; p_k(f,t)g_{1k}(f,t)df\,dt, \tag{9}$$

where the summation is carried out over the picture area. Figure 7(a) and 7(b) shows the result of evaluating equation (9) for the filter families derived from the two dominant lines of figure 1(c). The output is plotted as a function of order factor b_k' (see Section 1.1). The lines are detected, as in Paper 1, by removing a running mean, thinning and thresholding these plots.

3.2 The clean spectrogram

After detection, the time variation can be restored to the line family these can be plotted again as a spectrogram. Figure 8(a) and 8(b) show the two families detected in figure 1(c) restored in this manner. These should be compared to the spectrograms for figure 9(a) and 9(b) which result from processing the separate sources alone.

The threshold in line detection for the combined source analysis is chosen to be just above the level at which one false line would be detected as judged by the lines detected in the single source case.

The performance for the example shown appears to be only about 2 dB down on the single source case judged by this line detection criterion. That is, in the single source case the threshold chosen can be set some 2 dB below the combined case without any false alarms (i.e., false lines) appearing.

4. CONCLUDING REMARKS

The matched-filter family-template approach appears to be very useful in sorting out signatures produced by non-stationary line sources of the prescribed types. By normalising the filters to the measured background noise, rather than assuming it is white, it should be possible to further improve the detection performance.

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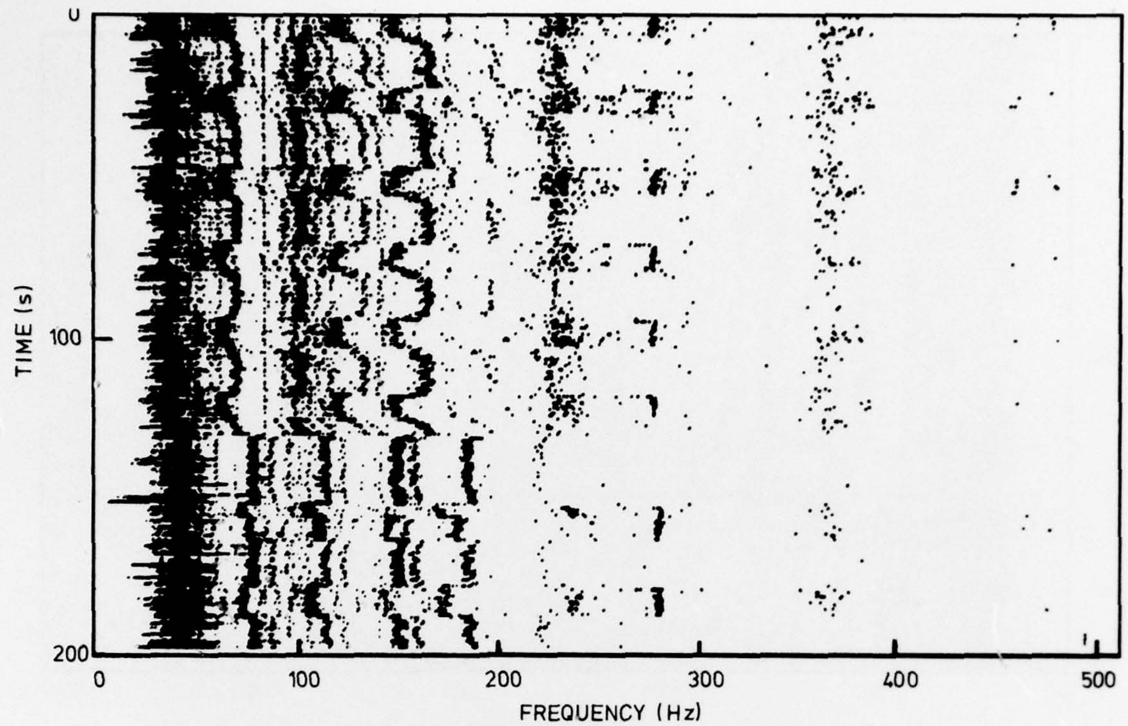


Figure 1(a). Spectrogram of source number 1. The broken line near 300 Hz is a 'fan' line.

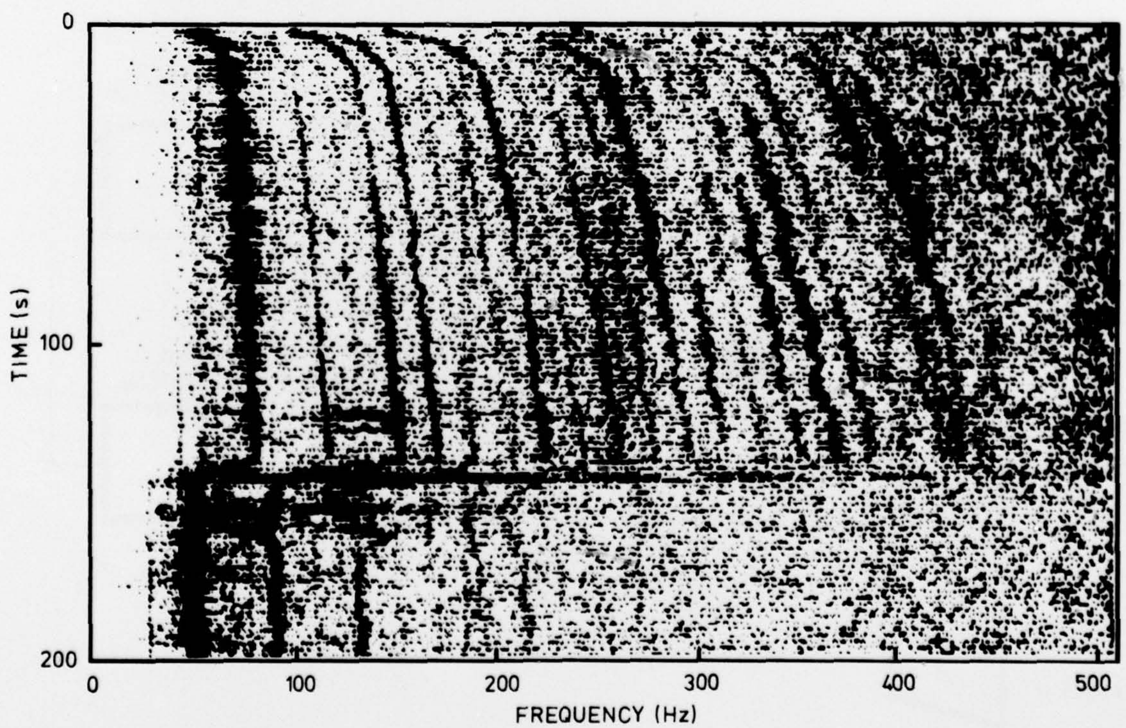


Figure 1(b). Spectrogram of source number 2.

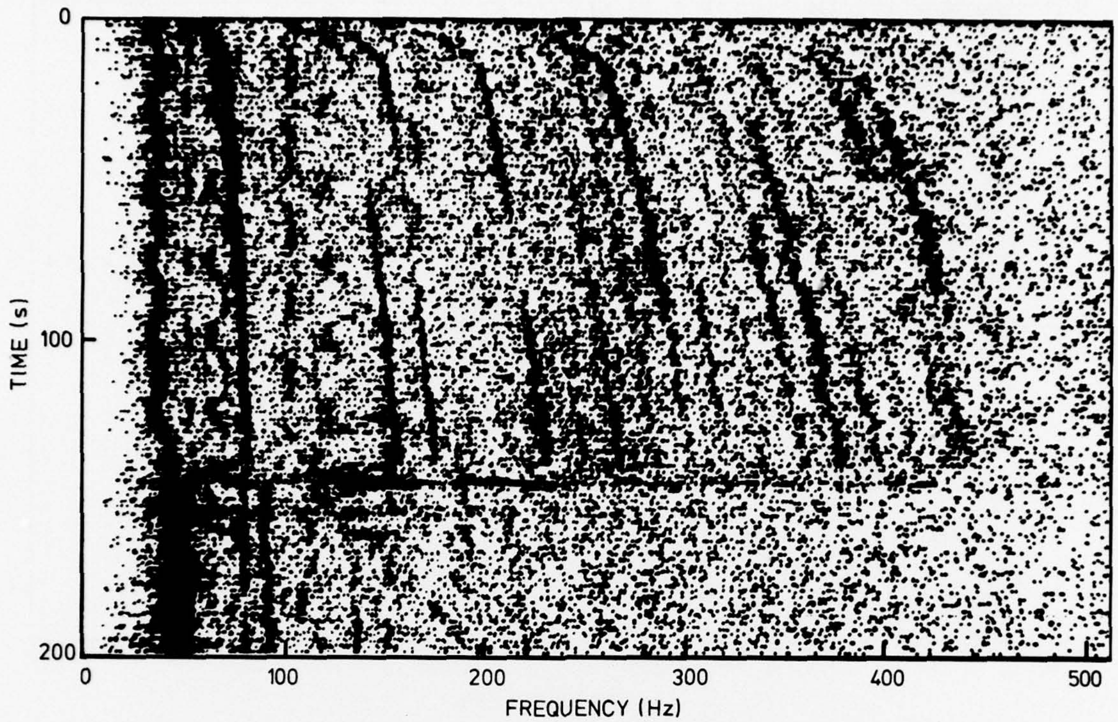


Figure 1(c). Spectrogram of combined sources

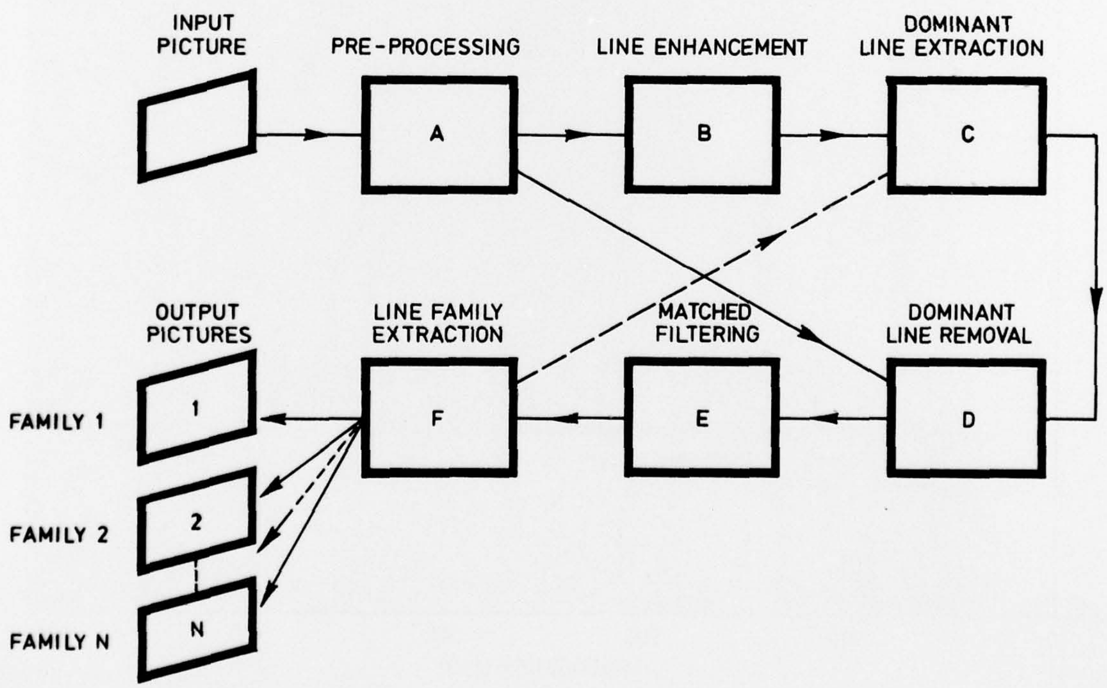


Figure 2. The signature separation process

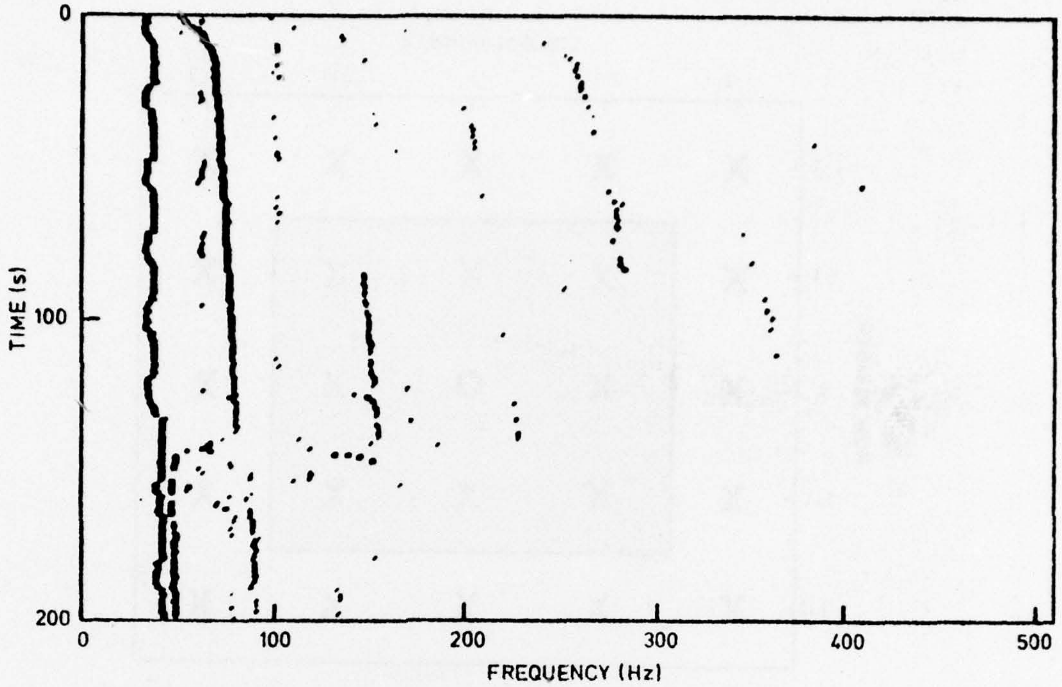


Figure 3(a). Thresholded combined spectrogram

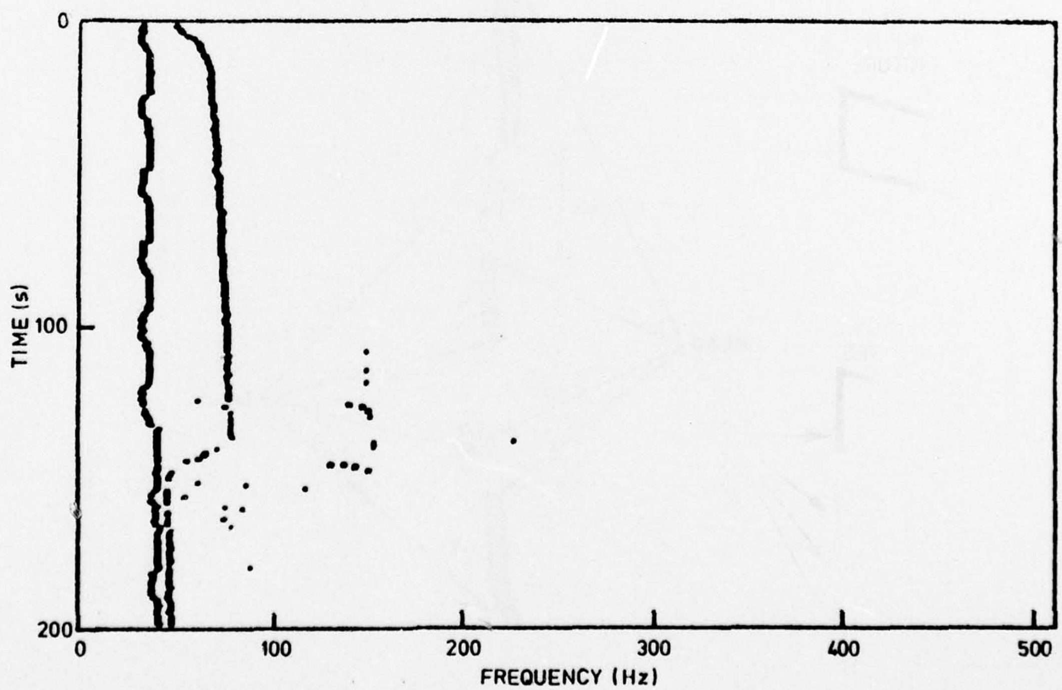


Figure 3(b). Thresholded spectrogram after line enhancement

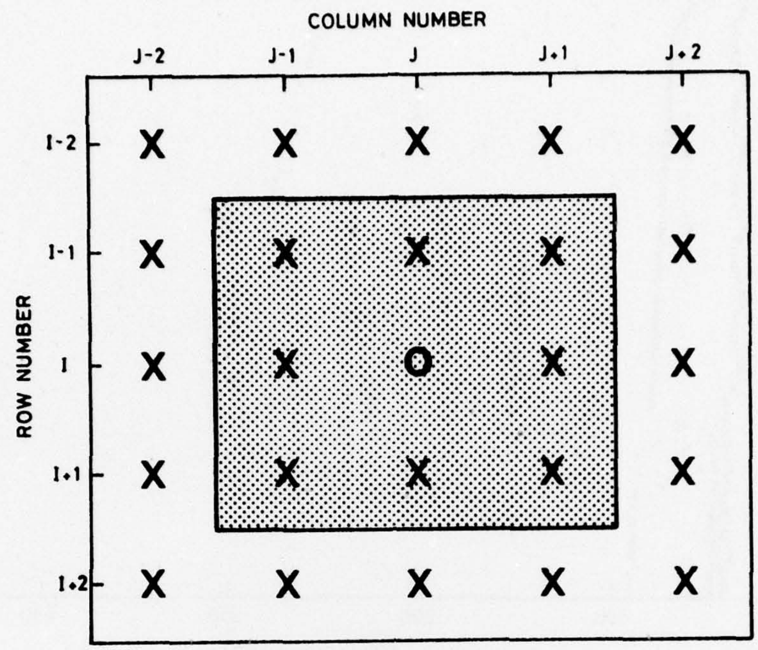


Figure 4(a). Definition of 'primary neighbours'

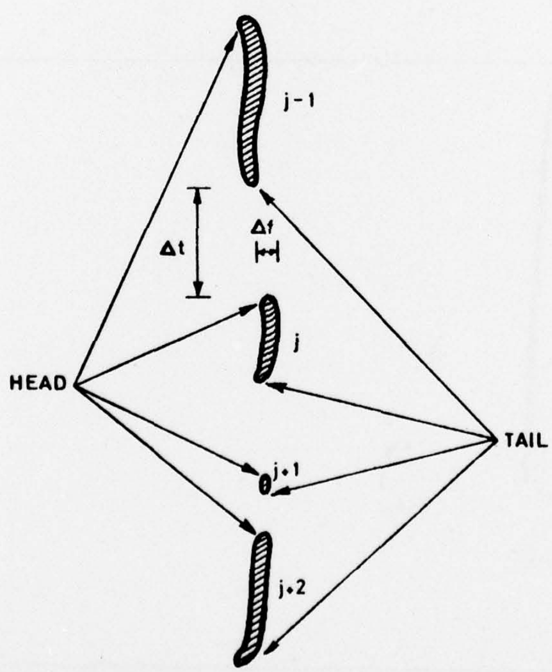
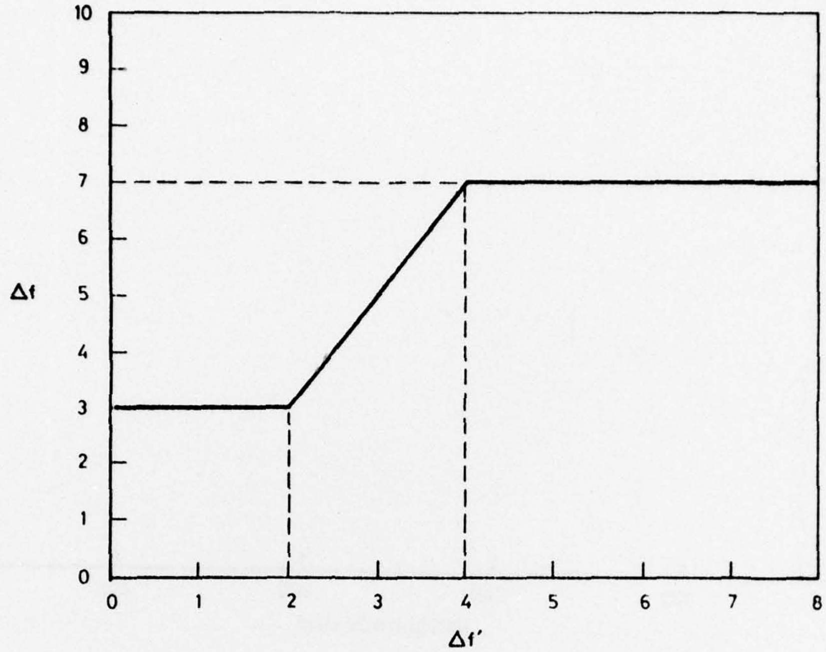


Figure 4(b). Mega-group searching



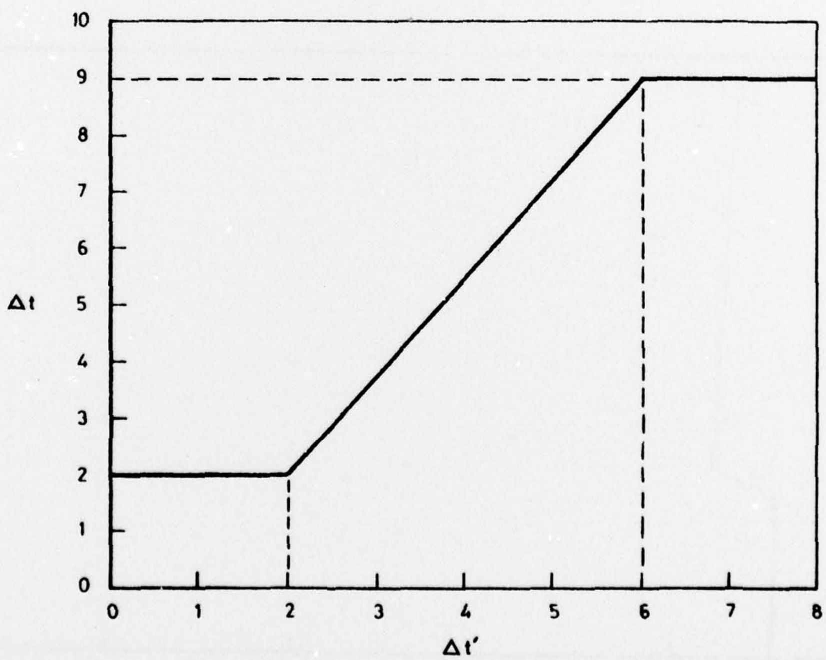


Figure 5. Frequency/time weighting used in search

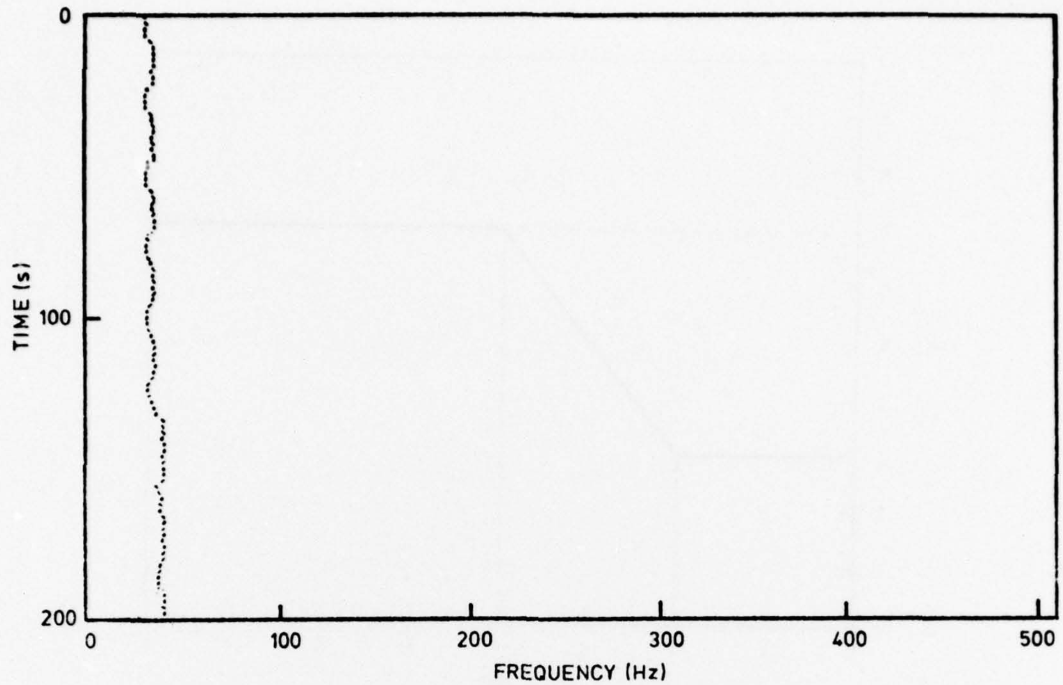


Figure 6(a). Dominant template for source 1

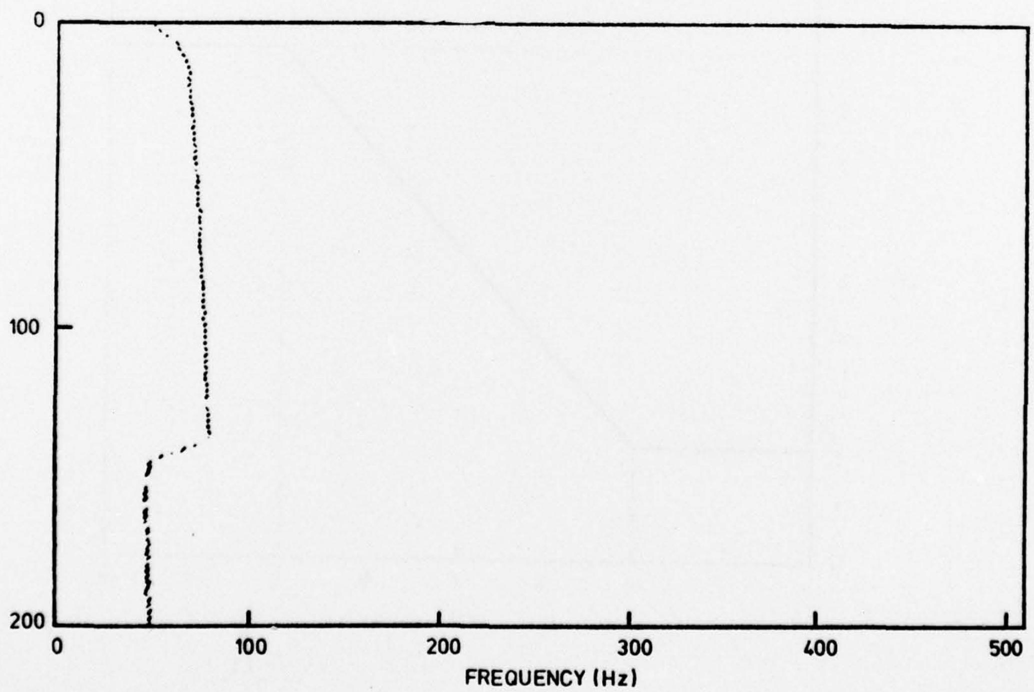


Figure 6(b). Dominant template for source 2

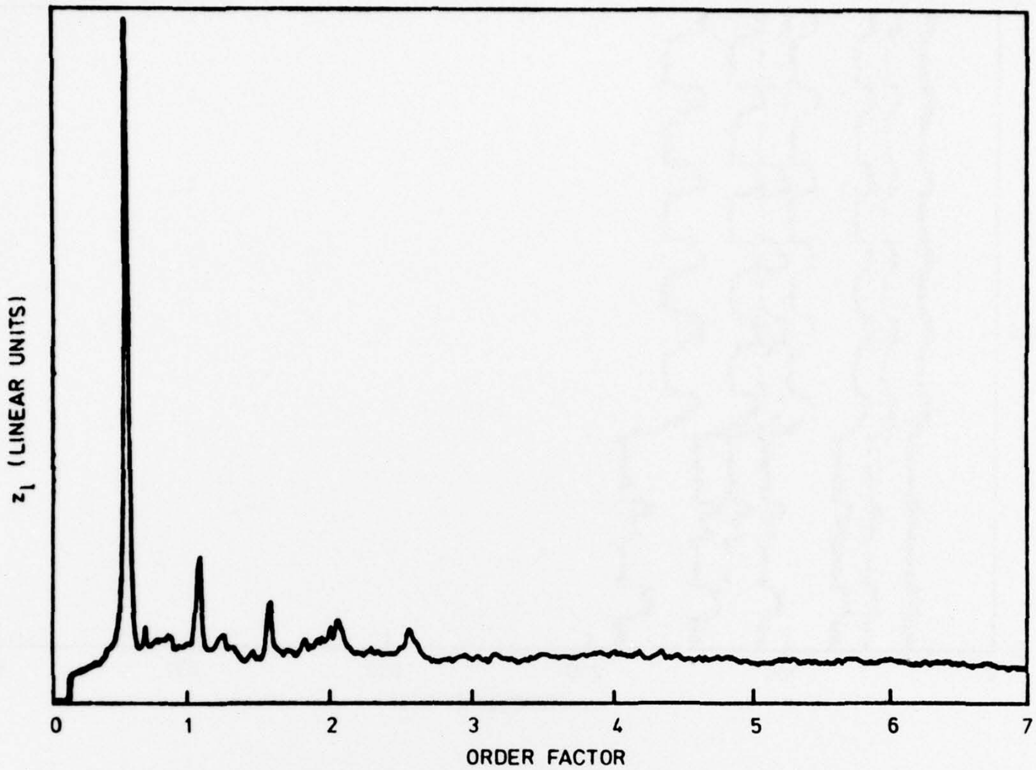


Figure 7(a). Matched filter output for source 1

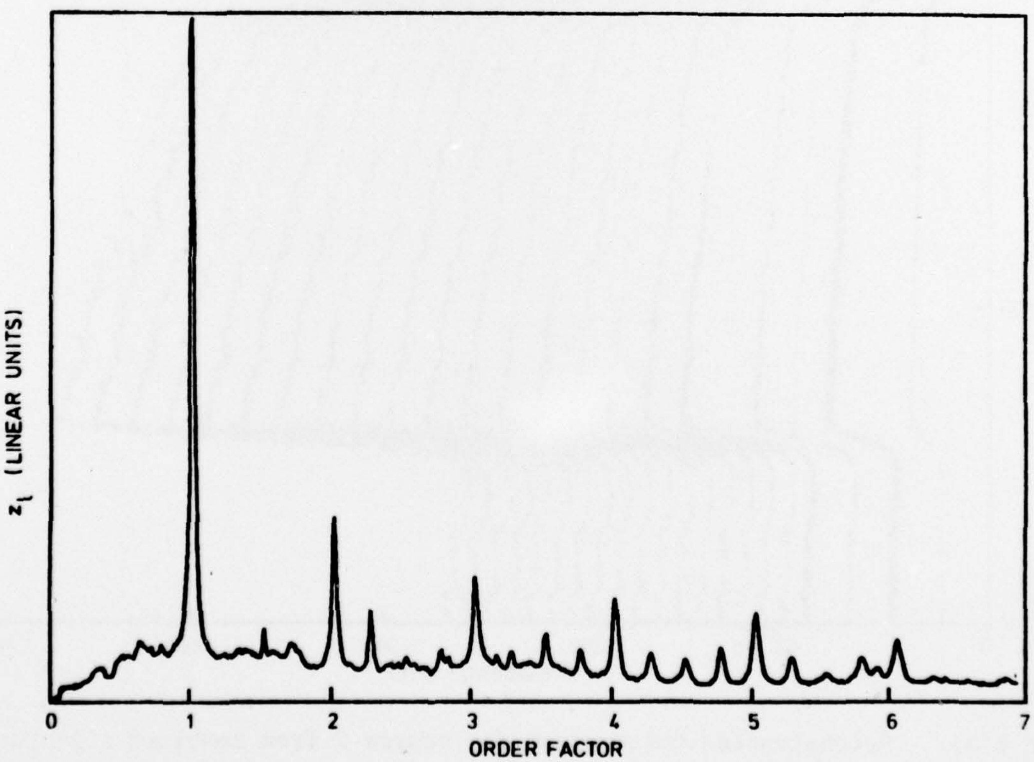


Figure 7(b). Matched filter output for source 2

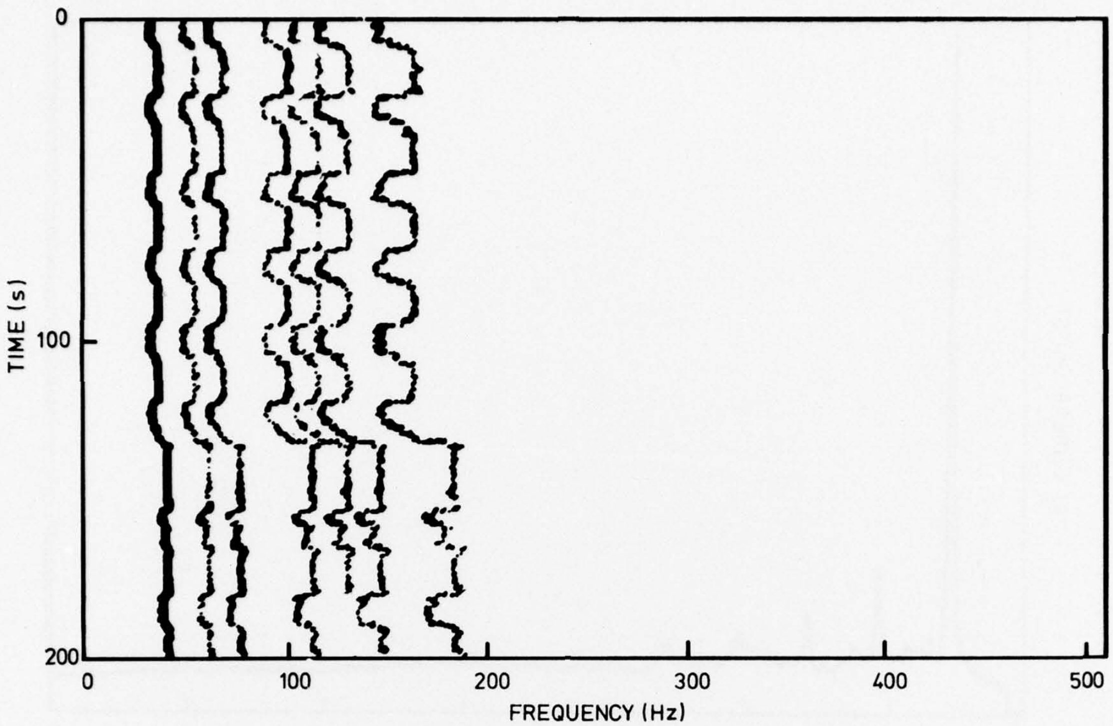


Figure 8(a). Reconstructed spectrogram for source 1 from combined signature analysis

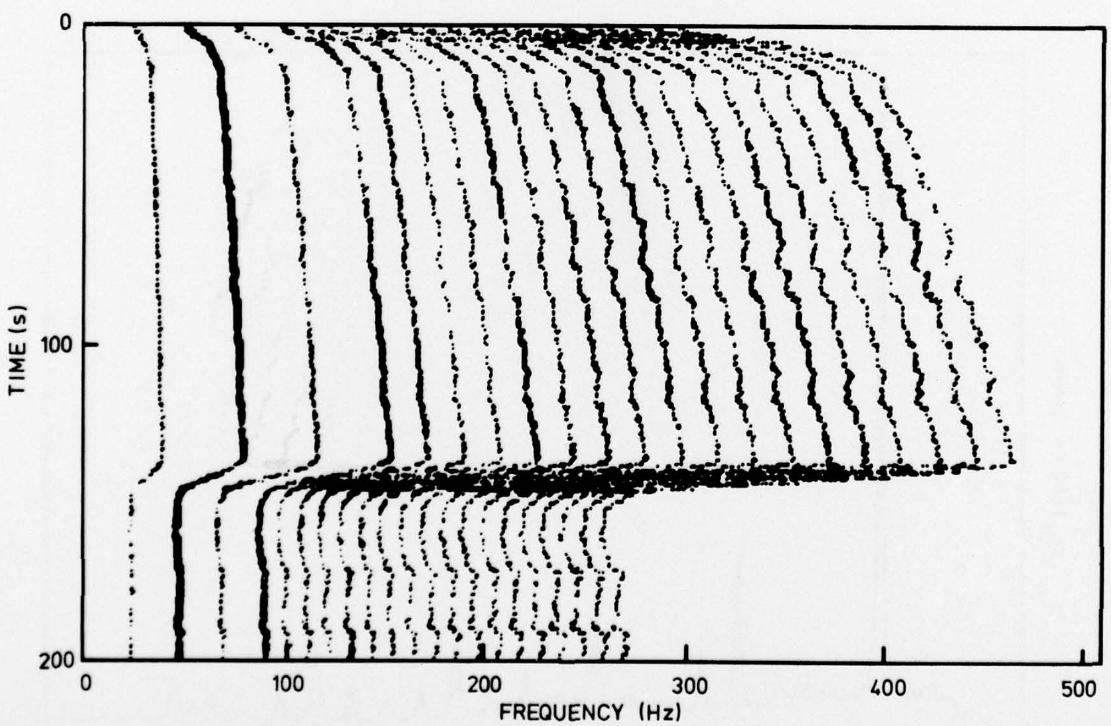


Figure 8(b). Reconstructed spectrogram for source 2 from combined signature analysis

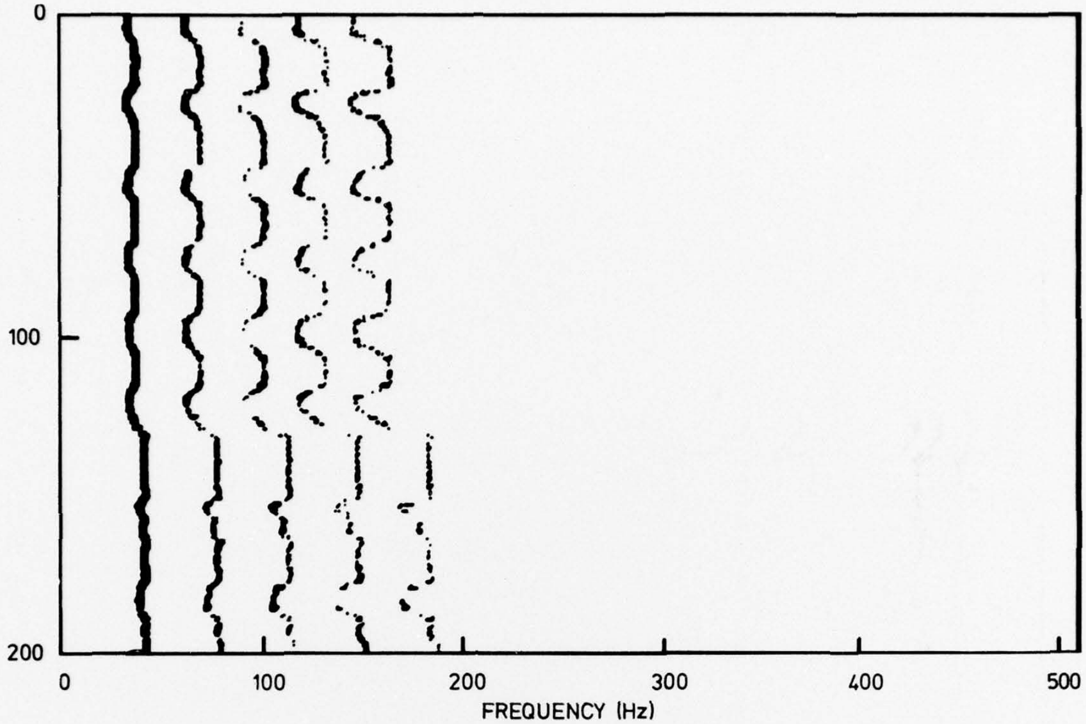


Figure 9(a). Reconstructed spectrogram for source 1 from single signature analysis

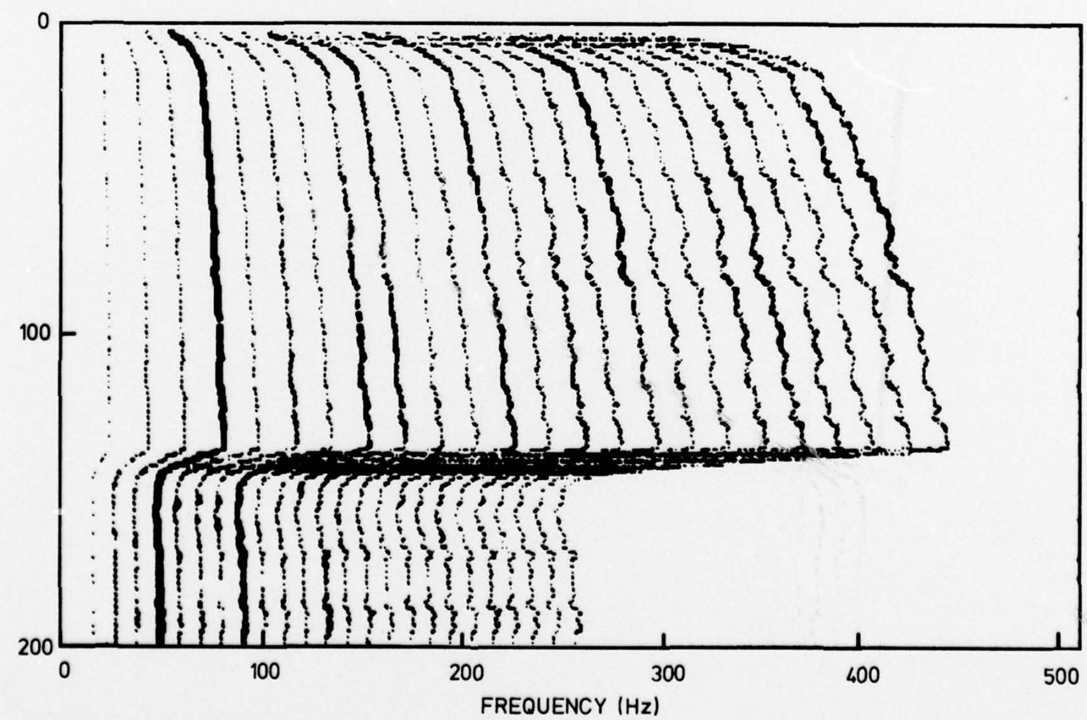


Figure 9(b). Reconstructed spectrogram for source 2 from single signature analysis

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